QuakeSim: Efficient Modeling of Sensor Web Data in a Web Services Environment

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***Abstract*- QuakeSim is a project to develop a modeling environment for studying earthquake processes using a web services environment. The multi-scale nature of earthquakes requires integrating many data types and models to fully simulate and understand the earthquake process. QuakeSim focuses on modeling interseismic processes and the multiple data types that must be ingested include spaceborne GPS and InSAR data, geological fault data, and seismicity data. QuakeSim federates data from these multiple sources and integrates the databases with modeling applications. Modeling applications include various boundary element, finite element, and analytic applications, which run on a range of platforms including desktop and high end computers. Because the models are complex and compute intensive we are using the Columbia computer located at NASA Ames to integrate and run software programs to improve our understanding of the solid Earth and earthquake processes. The complementary software programs are used to simulate interacting earthquake fault systems, model nucleation and slip on faults, and calculate run-up and inundation from tsunamis generated by offshore earthquakes. QuakeSim also applies pattern recognition techniques to real and simulated data to elucidate subtle features in the processes.**

I. INTRODUCTION

QuakeSim merges three approaches to develop an environment for improving our understanding of earthquake processes. We have developed computational infrastructure in the form of a web services portal environment that accesses compute resources, modeling, simulation, and analysis tools, and data. QuakeSim focuses on modeling the interseismic process, or the strain leading up to and following the earthquakes, rather than the earthquakes themselves. Any technique in earthquake forecasting requires an understanding of the interseismic process. Multiple data types are required for modeling interseismic processes, making up a sensor web of data sources. QuakeSim has been developed with an interest toward ingesting spaceborne deformation data in the form of GPS and InSAR data. We also include seismicity and geological fault data. The complexity of the models drive the need for high performance computing resources and as such we are developing grid services for interfacing the portal with various supercomputers at NASA Ames, JPL, and the NSF TerraGrid. We are also developing QuakeSim to handle and model the large volumes of crustal deformation data that will result from NASA's DESDynI mission.

II. DESDYNI

DESDynI (Deformation, Ecosystem Structure, and Dynamics of Ice) is a mission recommended by the National

Research Council Earth Science and Applications from Space Committee, commonly known as the Earth Science Decadal Survey [1]. It consists of two sensors that provide observations for solid Earth (surface deformation), Ecosystems (terrestrial vegetation structure), and climate (ice dynamics). It is a five-year mission with a frequent revisit on the order of 8-days. The two instruments are an L-band synthetic aperture radar operated as a repeat-pass interferometer (InSAR) with multiple polarizations, and a multiple-beam lidar operating in the infrared with a spatial resolution of 25 meters and a canopy height accuracy of 1 m.

The mission goals and scientific objectives for DESDynI are to:

1. Determine the likelihood of earthquakes, volcanic eruptions, and landslides.
2. Characterize the effects of changing climate and land use on species habitats and carbon budget.
3. Predict the response of ice sheets to climate change and impact on sea level.
4. Monitor the migration of fluids associated with hydrocarbon production and groundwater resources.

The mission addresses several challenges faced by our nation and globally. The US annualized losses from earthquakes are $4.4 B/yr, yet current hazard maps have an outlook of 30–50 years over hundreds of square kilometers. Measurement of surface deformation will yield insight into strain accumulation associated with earthquakes, and magma movement associated with volcanoes. The rate of increase of atmospheric carbon over the past century is unprecedented at least during the last 20,000 years. The structure of ecosystems is a key feature that enables quantification of carbon storage. Ice sheets and glaciers are exhibiting dramatic changes that are of significant concern for science and international policy. These indicators of climate remain one of the most under-sampled domains in the system. Additionally, management of our hydrological resources is applicable to every state in the union.

For DESDynI the deformation objectives for solid Earth and cryosphere must balanced against the ecosystem structure mission objectives in the mission design. Such trades include orbit repeat interval, coverage, and radar modes. Maximizing the coverage of the lidar observations drives the need for a longer repeat interval, while the deformation objectives require a more rapid repeat with the radar. Different radar modes such as quad-pol or single pol and scanSAR versus strip map mode change the coverage and the data volumes. The high data volumes, on the order of 650 GB/day drive the need for a new paradigm for data processing. There is also a need to balance systematic science observations with response to events such as earthquakes or volcanic eruptions.

The focus of QuakeSim for DESDynI is on addressing the solid Earth deformation science, particularly for the earthquake problem. QuakeSim is being used to develop the solid Earth observational needs for DESDynI and also serves as a prototype for establishing the computational infrastructure for science analysis and interpretation once the mission flies.

III. DEFORMATION SCIENCE REQUIREMENTS

As mentioned, one of the mission goals for DESDynI is to *determine the likelihood of earthquake, volcanic eruptions, and landslides and quantify the magnitude of events.* Any of the requirements that flow from the mission goals that address earthquakes are related to QuakeSim. The QuakeSim relevant science objective that flows from the mission goals is to *characterize the nature of deformation at plate boundaries and the implications for earthquake hazards*. Doing so requires the DESDynI relevant observations, which are to *measure surface deformation* and *measure surface disruption*. Meeting the science objective of characterizing the nature of deformation at plate boundaries and implications for seismic hazards requires models to be coupled to the observations. The goal of quakesim is to make a seamless modeling and data environment for improving our understanding of earthquakes.

We are using QuakeSim to validate that DESDynI will meet the earthquake science objectives, assess the quality of DESDynI science products, and understand observation noise and how it propagates to the science products. We will be constructing deformation baseline models and will use the LA region as a starting point, because of the complexity of faults and anthropogenic effects. From the deformation models we will study the sensitivity of the deformation to secular fault motions, aquifer subsidence, earthquake displacements and transient motions. From the model output will construct synthetic interferograms and time series and will interface these with the QuakeSim applications. We will add atmospheric and other noise and invert the synthetic data to understand our ability to recover fault parameters from the observations.

A. Repeat Interval

As mentioned, there is a trade between the frequent repeat interval required for deformation processes and the longer interval driven by a requirement for dense lidar coverage. In order to understand the impact of InSAR sampling interval on the discrimination of postseismic processes we generate time dependent postseismic surface deformation with 1 cm error from an ensemble of synthetic earthquakes. We study a linear combination of logarithmic afterslip and exponential decay relaxation. Coseismic and postseismic slip and the time constants for postseismic processes were generated from random distributions based on published postseismic parameters. A time series with parameter partials was generated for each synthetic event and transformed into estimation errors. We consider a synthetic event to be successfully resolved if the estimated amplitudes for both afterslip and relaxation have formal relative error less than half the larger of the two amplitudes. For two years of observations following an event, using an 8-day repeat as the nominal design we lose 7 per cent of the resolved events by changing to a 14-day repeat, and 30 per cent by changing to a 45-day repeat (Fig. 1). If we consider a half-year

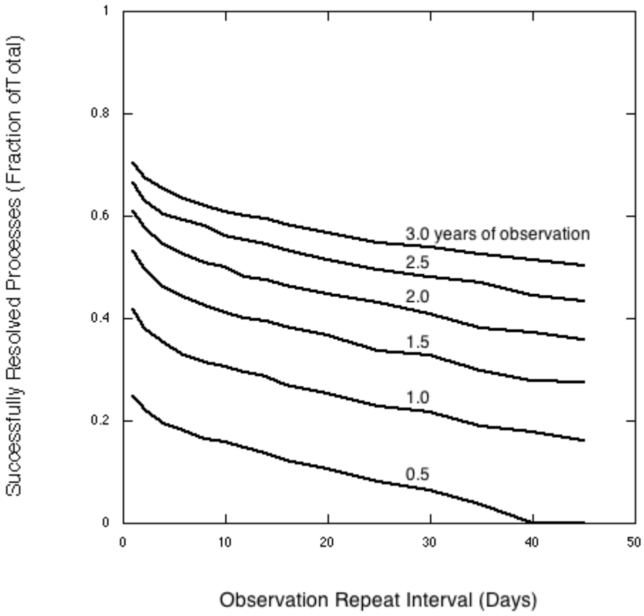

Fig. 1. Repeat interval and successfully resolved processes for damaging earthquakes (M>6).

observation time and 8-day repeat, we will fail to resolve 67 per cent of the nominal resolved cases, 73 per cent for 14-day repeat. For a 45-day repeat we are unable to resolve events after six months. A rapid response time of six months drives a need for an 8-day orbit. A 14-day repeat is acceptable for mechanisms to be determined after two years, however ice sheet grounding line studies require the observation repeat interval to be out of phase with the tides, driving a maximum allowable repeat interval of 12 days [2].

B. *3D Vector Deformation*

Discrimination of earthquake processes also drives a need for 3D vector deformation. One look provides deformation along the line-of-sight to the spacecraft. Inversion for fault parameters with one look results in a non-unique solution. 3D vector deformation requires a combination of ascending/descending and right/left looks. QuakeSim can be used to understand the sensitivity of look angles to uniqueness of the solutions. We can propagate the errors of sensitivity analysis.

IV. Data Volume and Grid Computing

The data volume from DESDynI is an order of magnitude greater than existing and planned missions (Fig. 2). Once downlinked the data must be moved to a processing facility and then distributed once processed. The mission will produce a minimum of 650 GB of data per day. If data downlink bandwidth limitations are overcome raw data production will be greater than 1 TB/day. The sheer volumes of data will require routine automated data processing on supercomputers. Data and products must be transported to and from the supercomputing resources and distributed for further processing and analysis. QuakeSim, is intended to establish infrastructure for the upcoming DESDynI mission

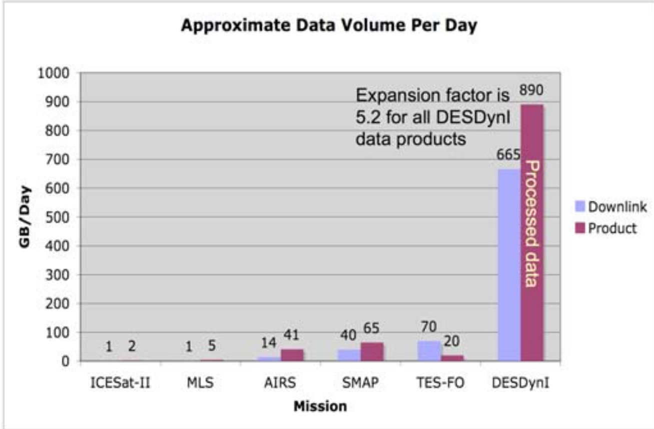

Fig. 2 Data rates for various Earth science missions.

as well as other potential missions.

We are building upon our Grid of Grids approach, which includes the development of extensive Geographical Information System based Data Grid services. We are extending our earlier approach of integrating the Data Grid components with improved Execution Grid services to interact with high-end computing resources. Our first targets for deploying these services are the Cosmos computer cluster at JPL, the NSF TerraGrid and the Columbia computer at NASA Ames.

The service architecture we have adopted is useful for running relatively small simulation problems but will need major enhancements to interact securely with the batch schedulers used by Columbia and other high-end supercomputers. Rather than developing this from scratch, we are integrating our approach with the Globus toolkit and services. The classic grid is Globus used by the National Science Foundation TerraGrid, and Open Science Grid (http://www.globus.org). The Globus Toolkit is an open source software toolkit for building Grid systems and applications. The “Grid” allows people to share computing power, applications, and databases across boundaries without sacrificing local autonomy. Globus provides the following relevant to QuakeSim:

- A secure remote execution and job management service (GRAM) that has bindings to several queuing systems (PBS, LSF, LoadLeveler, etc);
- Remote file management and file transfer (GridFTP);
- Information services (MDS);
- A single sign-on security environment (GSI) that enables limited delegation (useful, for example in GridFTP third-party file transfers); and
- A client programming API (the Java COG Kit) for its services. The Java COG has been used by the QuakeSim portal and related projects to provide access to the NSF TeraGrid.

Adopting Globus will provide several important features missing from the current command-line based system. The COG provides a rich client development environment that

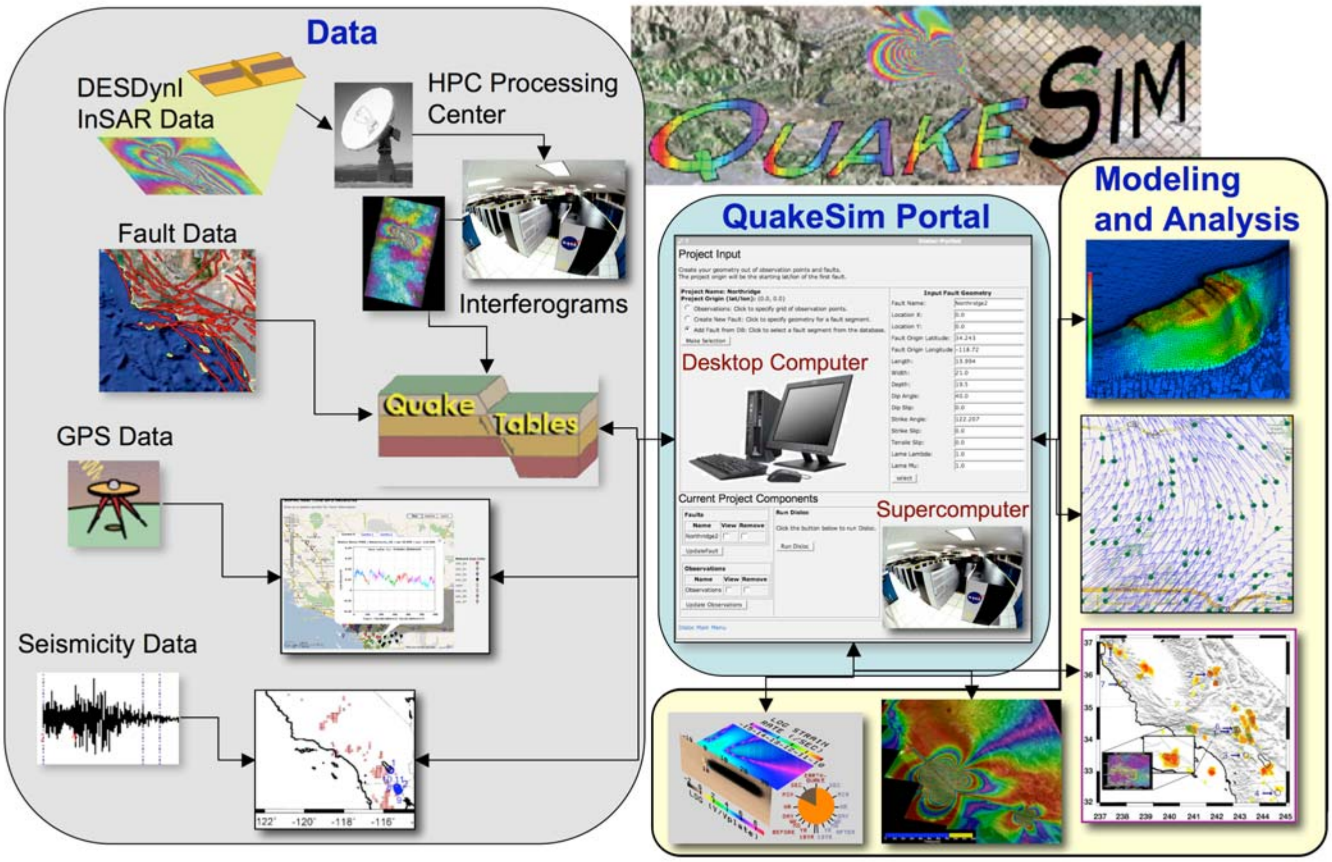

Fig. 3. QuakeSim end-to-end flow showing data sources, portal interface, and modeling and analysis output.

allows us to build graphical user interfaces as well as command line tools. The COG also supports the creation of graph-based workflows for chaining together several operations. The GRAM service supports multiple scheduling/queuing systems and provides an API for programmatically creating batch scripts that is independent of the queuing system. GridFTP supports third-party transfers in addition to uploads and downloads. This allows us to directly transfer files between two backend computers from a portal server. Globus provides optional information services (MDS) that can be used to access machine information that can be displayed to the user or used internally to assist with job submission decisions. Globus services can be used to set up cross-realm authentication. For example, services running at NASA JPL can be configured to accept user credentials signed by the NASA ARC Certificate Authority. We can take advantage of numerous external projects (such as Kepler and Condor-G) for workflow composition and high throughput computing. Though we are using globus for our approach, we have found that tailoring of the approach for each system has been needed.

V. DISTRIBUTED COMPUTING INFRASTRUCTURE

QuakeSim's current distributed computing infrastructure consists of Web services interacting with a clients in a component-based Web portal (Fig. 3). The Web services provide access to data (particularly fault models) and application codes through well-defined programming interfaces (expressed in WSDL). The QuakeSim portal is a graphical user interface that provides the following capabilities:

(1) Allows the user to couple databases with simulation codes. This is typically done in the input file creation process, in which users select desired fault models that will be used in the simulation from our fault database. GPS data sources are also supported.
(2) Assists users with setting up the complicated input files used by the codes.
(3) Allows the user to track the progress of running jobs.
(4) Allows the user to do simple plotting to inspect results, such as finite element meshes and calculated surface stresses.
(5) Allows the user to create and manage archives of jobs by storing metadata (all parameters used, times submitted, simple text descriptions) generated by the user's interactions with the portal. This allows the user to know exactly how a particular results was obtained and to quickly modify and resubmit it if desired.

(6) Allows the user to download output files created by a particular run.

We recently released version 2.0 of the QuakeSim portal. We use the JSR 168 portlet-complian GridSphere container, which is a popular product in the science gateway community. GridSphere enables developers to quickly develop and package third-party portlet web applications that can be run and administered within the GridSphere portlet container. It is used by the Open Grid Computing Environment Project, the Scripps GPS Explorer portal, and many TeraGrid Science Gateways. All portlets are developed using Java Server Faces (JSF). QuakeSim 2.0 has improved the richness of interfaces (Figure 2). We make use of Google Maps, YUI JavaScript Libraries, and BFO Plotting libraries for meshes.

VI. QUAKETABLES DATABASE

The QuakeTables database is part of the QuakeSim environment. Currently, QuakeTables houses paleoseismic and fault data that can be ingested into QuakeSim applications. We are expanding the database to include GPS velocities and interferograms processed from Synthetic Aperture Radar data. It is a challenge to convert data, particulary those collected and reported by a variety of means into standard data for modeling applications.

In QuakeSim applications we model fault activity such as rate of strain accumulation or offset related to earthquakes over a finite fault segment. Therefore, the modeler is interested in the general fault characteristics, such as geometry and average rate of slip with an associated uncertainty. Paleoseismic data and results are typically reported in scientific publications and there is no standard format or method for this reporting. Typically a geologist digs a trench across a fault and looks for disrupted layers and carbon samples within these disrupted layers. The samples are carbon dated, and ultimately the geologist publishes a paper with information on a particular earthquake rupture, or sequence of ruptures for a single point on a fault. Alternatively, there may be measurements or models to estimate fault parameters as a result of the occurrence of an earthquake. In order to ingest this information into a model then, judgment must be exercised as to how to extrapolate this information along the length of a fault segment. We have expended considerable effort in combing through the literature and other existing databases, online or off, to include as much information as possible about the faults in California in the QuakeTables database.

For many faults there are multiple interpretations. The purpose of QuakeTables is to standardize data for modelers and allow the modeler to further refine interpretations about faults. As such, then, QuakeTables does not house one single, self-consistent, fault model for California. Rather, it houses the many different interpretations, which can be many even for a single earthquake. It is therefore important for the user to be able to access a self-consistent set of faults for their model and to be able to trace the fault segment recorded in the database back to the original reference.

Another issue is that different applications may use parameters that are reported in different ways. For example, slip on a fault can be reported in Cartesian or polar coordinates. As a result, we have also created mathematical relationships between fault data items to ensure the consistency and semantic integrity of the data. The QuakeTables fault database also includes entries for including uncertainties on the data. The current design of QuakeTables allows for rectangular faults, which is consistent with the modeling applications.

One important requirement for the new QuakeTables design is its capability to store data from different data sources and keep it in its original format along with any calculated or derived datasets based on this original set. This feature was implemented using two different dataset representations within QuakeTables The first is DataSet, which are the original datasets by authors in their own format. These sets are stored in dynamic tables to preserve their original format. This type of dataset could also be snapshots of specific data that people want to preserve in a specific format. For example, we find that in carrying out pattern recognition of seismicity, the seismic catalog is occasionally updated and earthquakes are inserted, removed, or their magnitude or location is changed. The previous catalogue is no longer available, and these changes can impact our results. Hence we want to store all versions of the "standard" seismic catalogue. The other data representation is QTSet, which is a dataset that is derived from 'DataSet' and conforms to the QuakeTables format that is used by simulation programs. Each QTSet is linked to its original DataSet, and a DataSet could have multiple QTSets. Since DataSets are originally public domain, QTSets could be set to public or private to users or groups of users.

QuakeTables now also includes radar interferograms. The user can browse the database. The browser shows a thumbnail of the interferogram, as well as the title and description. The user can download the interferogram, or view the image in google maps. Our next step is to interface the interferogram with the deformation analysis applications.

VII. APPLICATIONS

Our QuakeSim applications include traditional high performance software as well as data analysis and assimilation codes. The high-performance modeling applications include GeoFEST [3], a finite element model that simulates stresses associated with earthquake faults, Virtual California [4], which simulates large, interacting fault systems, and PARK [5], which simulates complete earthquake cycles and earthquake interaction. The portal also contains Disloc, which models surface deformation from faults within an elastic half-space, and Simplex, which is an inversion application, which finds the optical dislocation model of fault slip from GPS and InSAR deformation data [6]. Analysis methods include Pattern Informatics [7], which examines seismic archives to forecast geographic regions of future high probability for intense earthquakes, and RDAHMM [8], a time series analysis application that can be used to determine state changes in instrument signals (such as generated by Global Positioning System arrays). The portal also has a mesh generation tool and tool to filter GPS time series data. We expand on some of the applications here.

A. Virtual California

Virtual California (VC) is a numerical simulation program for studying the system-level dynamics of the vertical strike-slip fault configuration in California [9,10]. The majority of plate boundary deformation in California is accommodated by slip (i.e. earthquakes) on the strike-slip faults included in the Virtual California models (Figure 5).

Virtual California uses topologically realistic networks of independent fault segments that are mediated by elastic interactions. Virtual California is a backslip model, inasmuch as the plate tectonic stress increases are produced by means of applying a negative (backslip) velocity to each segment whose magnitude is that of the long-term rate of slip on the segment. Since "positive slip" reduces the stress on a fault segment, "negative slip" due to the backslip increases the stress. On each time step, all faults are checked to determine whether the shear stress has reached the failure threshold. Once at least one segment reaches the threshold, the "long time steps" stop, and "short (failure) time steps" (a.k.a. Monte Carlo Sweeps, or mcs) begin. An mcs begins with a check of each site to determine whether it has failed, followed by a parallel updating of each segment. An update of a segment consists of increasing the sudden seismic slip on each segment so that the stress of the segment, considered in isolation, drops to a residual value, plus or minus a random overshoot/undershoot. The elastic stress on all segments is then recalculated, and another mcs is carried out. This iterative process repeats until all segments are below the failure threshold, at which time the mcs time steps cease and the long plate tectonic time steps begin again.

Virtual California also includes a stress-dependent precursory slip, or stress leakage of the type that has been observed in laboratory experiments by [9] and [10]. The physics of this process is that as the stress on a segment increases, a small amount of stable sliding occurs that is proportional to the level of the stress above the residual. Lab experiments and field data suggest that the frictional parameter alpha [8] is of the order of a few percent. Alpha is defined as the fraction of aseismic slip relative to total slip. Therefore, it may be possible to detect precursory signals before earthquakes using InSAR data from missions such as DESDynI. Virtual California simulations enable testing for precursory signals. Hence a focus is to analyze the magnitude and spatial distribution any precursory slip in the simulations.

B. GeoFEST

GeoFEST uses stress-displacement finite elements to model stress and flow in a realistic model of the Earth's crust and upper mantle in complex regions such as southern California, including the Los Angeles Basin. The model includes stress and strain due to the elastic response to an earthquake event in the region of the slipping fault, the time-dependent viscoelastic relaxation, and the net effects from a series of earthquakes. The physical domain may be two- or three-dimensional and may contain heterogeneous materials and an arbitrary network of faults. Finite element modeling in three dimensions allows faithful modeling of complex faulting geometry, inhomogeneous materials, realistic viscous flow, and a wide variety of fault slip models and boundary conditions. Because finite elements conform to (nearly) any surface geometry and support wide variations in mesh density, solutions may be made arbitrarily accurate with high computational efficiency.

GeoFEST runs in the high-performance domain of message-passing parallel computer systems [13] including the Columbia system at NASA Ames and the COSMOS system at JPL, among others. In includes the functions of the PYRAMID parallel adaptive mesh refinement library [14]. Source code is available with a no-fee license from Open Channel and it runs within the QuakeSim web-based problem-solving environment [15]. All documentation and links to Open Channel and the portal can be found at http://quakesim.org.

The primary quantity computed by GeoFEST is the displacement at each point in a domain. The stress tensor is also computed as a necessary byproduct. The computational domain represents a region of the earth's crust and possibly underlying mantle. It is typically a square or rectangular domain in map view, with a flat upper free surface and constant depth, but the domain may deviate from this. The only requirement is that it be a bounded 3D domain with appropriate surface boundary conditions to render the problem well defined. These boundary conditions may be specified as surface tractions and/or displacements, which are usually specified on all surfaces and at times on interior surfaces such as faults. Free surfaces have zero surface traction by definition. Faults are interior surfaces, and may have associated dislocation increments at set times. The solid domain may contain layers or other distributions of material with associated rheological properties.

Currently supported materials are isotropic, Newtonian elastic, Newtonian viscoelastic, and non-Newtonian power-law viscosity. Elastostatic solutions are supported, such as computing the displacements and stresses immediately caused by a specified slip distribution on a fault or finding the interior displacement and stress distribution due to a surface traction or displacement. These solutions are not time-dependent. Viscoelastic solutions, which are time dependent, are also supported, in which the material flows and relaxes in response to imposed stress, such as an earthquake event. One may compute the viscoelastic response to a single event, or to multiple events in a sequence. The sequence may be user-specified. Location-specific body forces are supported.

Boundary conditions and solutions apply to a finite-element discretized approximation to this domain. The domain is defined internally as a mesh of space-filling tetrahedral or hexahedral elements, with three components of displacement at each mesh node constituting the solution. Stress is computed for each element, and is element-wise constant for the current linear tetrahedral element type. Surface nodes carry special boundary conditions such as tractions or specified displacements. Nodes on faults are special split-nodes that define screw or tensile dislocation on the fault without perturbing the mesh geometry. Temporal evolution is by discrete time steps using an implicit solution technique, allowing large time steps without numerical instability.

C. Pattern Recognizers

The Pattern Informatics earthquake forecasting methodology is proving extremely successful. In the last six months five earthquakes above magnitude 5 have occurred in identified hotspots. The identified hotspots make up only 1.2% of the total map area of the forecast or the state of California. The approach is to minimize the forecast area, which is essentially the false alarm rate, while still detecting all the large earthquakes (maximizing the hit rate).

Our other pattern recognition technique, RDAHMM, which analyzed GPS time series data identified a reference frame error in the data processing introduced by a large earthquake in Siberia. RDAHMM, or Regularized Deterministic Hidden Markov Model, carries out time series analysis and mode detection in GPS and other signals. Examples of signals that RDAHMM can detect are ground subsidence from withdrawal of water from aquifers and earthquake co-seismic and post-seismic signals.

We have integrated the processing of GPS position time series data into the QuakeSim portal. By wrapping the RDAHMM time series analysis software as a web service filter, it is seamlessly integrated into work and data processing flows. Raw GPS data (1Hz) are converted to RYO (real-time) format and made available through a data server. Then data are passed through a series of filters that perform format conversion and station separation. Message passing is handled through NaradaBrokering. Finally, data are passed to the RDAHMM analysis application.

We have implemented an interface through which the RDAHMM software can be applied to archived daily GPS solutions to perform time series segmentation. Segmentation results are provided both graphically and through numerical descriptions of segmentations and fitted models, which are available for download. In addition, we have implemented a proof-of-concept Google maps interface to RDAHMM analysis of real-time streaming GPS data. The segmentation analysis is performed on the last ten minutes of real-time data, and then displayed graphically upon mouse-over in the Google maps interface

V. CONCLUSIONS

The GeoFEST finite element software is being used for supporting NASAís decadal survey DESDynI mission to establish requirements such as the need for 3D vector deformation. We are working solutions with both NASA Ames and JPL to add grid services so that QuakeSim can interface with Columbia and Cosmos. QuakeSim represents the first major user of Columbia that has identified Grid services and Condor G as a requirement for job launch. The QuakeTables database now includes InSAR interferograms. Analysis of Virtual California interacting fault systems shows that events on the southern San Andreas fault typically follow, but do not precede, events on the Eastern California Shear Zone. Other modeling work shows the need for adding complexity to the models and indicates that there is 1 mm/yr of postseismic motion still occurring from the 1906 San Francisco earthquake. QuakeSim is also being used in the classroom in geophysics and tectonics classes.

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